Indian J. Phys. 77B (6), 639-643 (2003)

AN INTERNATIONAL JOURNAL
IJP B

Theoretical analysis of a right isosceles triangular microstrip antenna on ferrite substrate

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Received 30 July 2003, accepted 19 September 2003

Abstract Radiation characteristics of a right isosceles triangular microstrip antenna (RITMA) structure on a biased ferrite substrate are investigated theoretically in this paper by applying Green's function and vector potential technique. The analysis is carried out in TM_{11} mode of excitation that predicts a larger bandwidth than similar antenna on a non-magnetic dielectric substrate Far field radiation patterns, impedance characteristics, quality factor and directivity of antenna are computed theoretically as a function of bias field strength Outcomes of present investigations may be applied in designing switchable and frequency agile ferrite RITMA structures.

Keywords : Microstrip antenna, Ferrites, circular polarization and radiation properties

PACS Nos. 84 40 Ba, 75 50 Gg

1. Introduction

A microstrip antenna consists of a metallic patch or an array of patches printed on a non-magnetic, low loss dielectric substrate with a large ground plane. Generally low bandwidth and low directive gain of these antennas restrict their application in several fields. Enough theoretical and experimental work on these antennas [1, 2] particularly on rectangular and circular geometries has been carried out but a little amount of work on triangular geometries has been reported. Most of this work on triangular geometries is limited up to Equilateral Triangular Microstrip Antenna [3,4]. Serious efforts have been made to improve the bandwidth and gain of microstrip antennas including application of low permittivity and electrically thick dielectric substrates. With the current interest in integrated antennas and microwave circuitry, advancements in thin film technology and availability of low loss commercial microwave ferrite substrates, many new possibilities have emerged for the control of antenna characteristics. Handerson *et al* [5] reported the use of a biased ferrite substrate to control patterns of a microstrip antenna while Das *et al* [6] tested microstrip antennas on unbiased ferrite substrate. Bladel [7] used inherent anisotropy and nonreciprocal properties of ferrite materials for antenna polarisation diversity. By forcing ferrite substrate into cutoff state under external biasing, beam steering [8], pattern shape control and radar cross-section (RCS) control [9] are also obtained. Shrivastava *et al* [10] investigated the effect of biasing magnetic field on tunability of a rectangular microstrip antenna while Dixit *et al* [11] applied ferrite substrates in array design.

This paper describes theoretical radiation properties of a right isosceles triangular microstrip antenna (RITMA) printed on a typical ferrite substrate $Ni_{1.062}Co_{0.02}Fe_{1.948}O_4$ by applying Green's function and vector potential technique and results are presented systematically.

2. Antenna geometry and coordinate system

A right isosceles triangular microstrip antenna with side lengths a, a and $\sqrt{2}a$ is considered lying in XY plane over a large ground plane with substrate thickness $(h << \lambda_0)$, substrate dielectric constant ε_r and relative permeability μ_r as shown in Figure (1a). The metal used for printing the radiating patch and the ground plane are nonmagnetic therefore the presence of external magnetic field only affects the ferrite material used as substrate for preparing microstrip antenna. So long as the substrate is

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electrically thin, electric field will be in z-direction (z axis is normal to patch geometry) and interior modes are quasi-discrete TM_{mn}

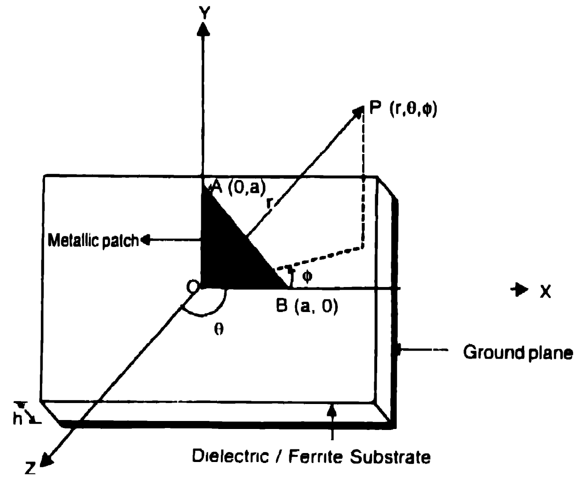

Figure1(a). Geometry of RITMA structure with coordinate system

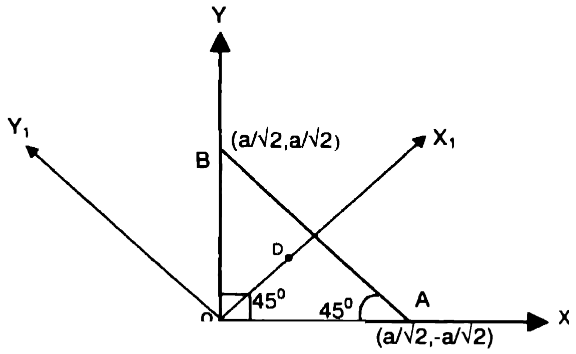

Figure1(b). Modified coordinate system on RITMA structure.

modes to z. The Green's function for the right isosceles triangular geometry will be given by [12] :

$$G(x,y|x_0,y_0) = \frac{j\omega\mu}{a} \frac{\sum_{m=0}^{\infty}\sum_{n=0}^{\infty} \sigma_m \sigma_n T(x_0,y_0) T(x,y)}{\left(m^2+n^2\right)\pi^2 - a^2 k^2} \quad (1)$$

where

$$T(x,y) = \cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{a}\right) + (-1)^{m+n}\cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{a}\right) \quad (2)$$

$$\sigma_i = \begin{cases} 1 & if \quad i=0 \\ 2 & if \quad otherwise \end{cases} \quad (3)$$

and

$$= k_0 \sqrt{\frac{\mu_{eff}\,\varepsilon_r (1 - j\tan\delta)}{\mu_0}} \quad (4)$$

Here c is the velocity of light and k_0 is the propagation constant in free space.

For the present analysis, an inset feed location is obtained for feeding this antenna. For this purpose, coordinate system shown in Figure 1(a) is rotated by an angle 45^0 in xy-plane as shown in Figure 1(b) and a proper feed location D (OD, 0) on modified X_1 axis is located in such a way that input impedance of antenna matches with that of feed line. The modified expression of $T(x, y)$ after rotating the coordinate system will be

$$T(x_1,y_1) = \cos\left(\frac{m\pi x_1}{a}\right)\cos\left(\frac{n\pi y_1}{a}\right) + (-1)^{m+n} \cos\left(\frac{m\pi x_1}{a}\right)\cos\left(\frac{n\pi y_1}{a}\right) \quad (5)$$

where

$$x = \frac{1}{\sqrt{2}}(x_1 - y_1) \quad \text{and} \quad y = \frac{1}{\sqrt{2}}(x_1 + y_1).$$

The effect of fringe fields is incorporated in the present analysis by replacing side length a of the patch by effective side length a_e, given by

$$a_e = a + \left| \frac{}{\sqrt{\varepsilon_r}} \right| 1.488. \quad (6)$$

Table 1. Computed antenna parameters of RITMA structure.

		Patch size (in meters)	Resonant frequency (GHz)	Quality factor (Q_t)	Band-width (%)	Directivity (in dB)
Normal substrate ε_r = 2.32, h = 0.0016 $\tan\delta$ = 0.001		0.05645	2.402 (Calculated)	141.68	0.499 (Calculated)	6.27 (Calculated)
			2.402 (Simulated)		0.500 (Simulated)	6.25 (Simulated)
Ferrite substrate ε_r = 14.78 h = 0.002 meter $\mu_0 M_s$ = 0.3 Tesla Ho = 0 .796 × 10^5 Amp/m	LHCP	0.026	1.2	20.01	3.533	4.859
	RHCP	0.026	7547	20.12	3.510	4.806

By applying eqs. (1) to (6), first the theoretical analysis of a RITMA structure on a low permittivity and low loss non-magnetic substrate ($\varepsilon_r = 2.32$, $\tan\delta = 0.001$) is carried out by using patch dimension $a = 0.05645$m and substrate thickness $h = 0.00159$m. These computed parameters are validated by comparing them with those parameters obtained with IE3D simulation software. The feed location under both these techniques is kept identical i.e. (26.87 mm, 0). The real part of computed and simulated input impedance at this feed location is close to 50 ohms. Some other computed antenna parameters are listed in Table-1. Computed and simulated variations of directive gain in upper hemisphere for ($\phi = 0$) plane are shown in Figure 2. A fairly good agreement between two curves validates this procedure of treating a RITMA structure.

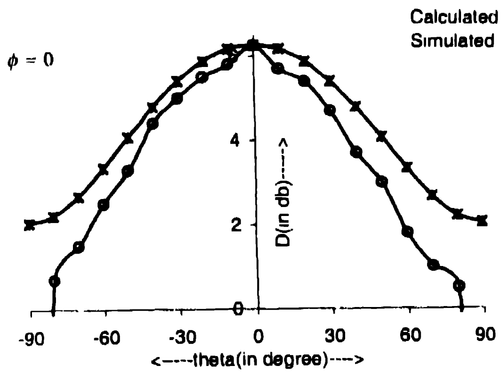

Figure 2. Comparison between computed and simulated E plane directive gain of antenna

Without changing the patch dimensions, the low loss non-magnetic substrate material used so far in this theoretical analysis, is replaced by ferrite material $Ni_{1.062}Co_{0.02}Fe_{1.948}O_4$. The substrate parameters of applied ferrite substrate are discussed elsewhere [13]. A ferrite slab may support various guided modes and these propagating modes get affected in the presence of applied magnetic bias field [14]. A stronger bias field may be obtained easily along the plane of antenna by placing two pole pieces of magnet in close contact with substrate. When propagation of electromagnetic waves takes place along this bias field in an infinite ferrite having two orthogonal feeds, two plane wave modes namely left hand circularly polarised (LHCP) mode and right hand circularly polarised (RHCP) mode generate. The effective permeability (μ_{eff}) of substrate material for these modes is calculated following [13]. The resonance frequency of RTMA structure on a biased ferrite substrate excited in TM_{mn} mode is given by

$$f_r = \frac{k_m c}{2\pi\varepsilon_r}\sqrt{\frac{\mu_0}{\mu_{eff}}} \tag{7}$$

with $k_m = \sqrt{2}\left(\dfrac{m\pi}{a_e}\right)$.

The variation of propagation constant of electromagnetic waves in the ferrite medium $\gamma\left[= \alpha + j\beta = j\omega\sqrt{\{\varepsilon_0\varepsilon_r\mu_0\mu_{eff}\}}\right]$ with operating frequency is shown in Figure 3. In RHCP mode, antenna does not operate in the range of frequency 4 GHz to 11 GHz because most of the power is converted into magnetostatic waves and a little power radiates as useful power in space. For LHCP mode, propagation constant increases as operating frequency of antenna increases. For the present work, computed propagation constants for RHCP and LHCP modes at operating frequency 1.5 GHz, are 15.81 and 25.13 per meter respectively.

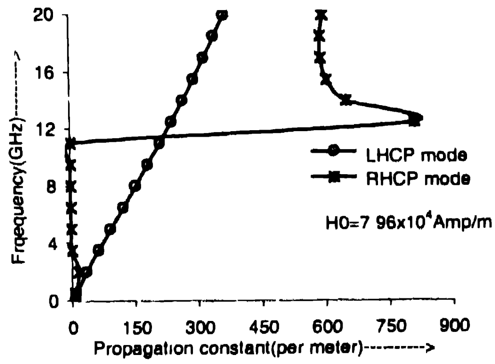

Figure 3. Variation of propagation constant of antenna with frequency.

The computed radiation characteristics of the RITMA structure are given in Table 2. It is clear from this table that the radiation intensity of antenna is maximum in the broad side direction for both ($\phi = 0$) and ($\phi = \pi/2$) planes and does not change even on application of external bias field. The half power beam width is calculated under unbiased and biased conditions which indicates that in ($\phi = 0$) plane, radiation patterns are nearly omni directional but in ($\phi = \pi/2$) plane, patterns becomes

Table 2. Computed radiation characteristics.

S No.	Pattern Characteristics	$\phi = 0$ plane	$\phi = \pi/2$ plane
	Direction of maximum intensity ($H_0 = 0$)		0°
	Direction of maximum intensity under biased condition ($H_0 = 7.96 \times 10^4$ Amp / m)		
3	Half Power Beam width ($H_0 = 0$)	Nearly omni directional	89°
4	Half Power Beam width under biased condition ($H_0 = 7.96 \times 104$ Amp / m)	**LHCP mode:** Nearly omni directional **RHCP mode:** Nearly omni directional	84° 80°
5	Direction of side lobe and back lobe if any ($H_0 = 0$)	-	-
6	Direction of side lobe and back lobe if any under biased condition ($H_0 = 7.96 \times 10^4$ Amp / m)	-	-

little more directional on applying bias field. No side lobes can be seen even on application of bias field.

3. Antenna input impedance and bandwidth

The knowledge of field configuration and impedance seen by the feed are important parameters for efficient use of microstrip elements. The expression for complex antenna impedance derived in TM_{mn} mode in term of voltage at the feed is

$$Z_{in}(f) = \frac{2j\omega\mu_0}{a_e^2}\sum_{m=1}^{4}\left[\sum_{n=1}^{4}\left[\left[\left(\cos\left(\frac{m\pi x_0}{a_e}\right)\cos\left(\frac{n\pi y_0}{a_e}\right)+\right.\right.\right.\right.$$

$$\left.\left.\left.\left.(-1)^{m+n}\cos\left(\frac{n\pi x_0}{a_e}\right)\cos\left(\frac{m\pi y_0}{a_e}\right)\right)^2\right]\Big/K^2-K_{mn}^2\right]\right].$$

The variation of real part of computed input impedance $\mathrm{Re}(Z_{in})$ of RITMA structure with frequency is shown in Figure 4. These variations are obtained by applying low permittivity substrate ($\varepsilon_r = 2.32$), unmagnetised ferrite substrate ($\varepsilon_r = 14.78$, $H_0 = 0$) and magnetised ferrite substrate with biased field ($H_0 = 7.96 \times 10^4$ Amp/m). Under the unbiased condition ($H_0 = 0$), ferrite based antenna structure behaves like a dielectric patch antenna designed on a high permittivity substrate materials since each of them have a single resonance peak. With non-magnetic low permittivity substrate, resonance peak is at 4.99 GHz, which shifts to 0.8 GHz for unbiased ferrite based microstrip antenna. On applying a D.C. bias field, the single resonance curve obtained with unbiased ferrite substrate divides in two resonance curves, one each for LHCP mode and RHCP mode with resonance frequencies 1.2 and 0.75 GHz respectively. The input impedance of antenna increases on increasing applied field strength as shown in figure (5). In LHCP mode it varies from 35.02 ohm to 57.23ohm indicating that antenna can operate efficiently in entire range of applied magnetic field without many reflections. In contrary in RHCP mode, a large variation in input impedance near off switch condition indicates that antenna can operate in a limited range of applied magnetic field *i.e.* between $H_0 = 1.592 \times 10^5$ Amp/m to 4.77×10^5 Amp/m.

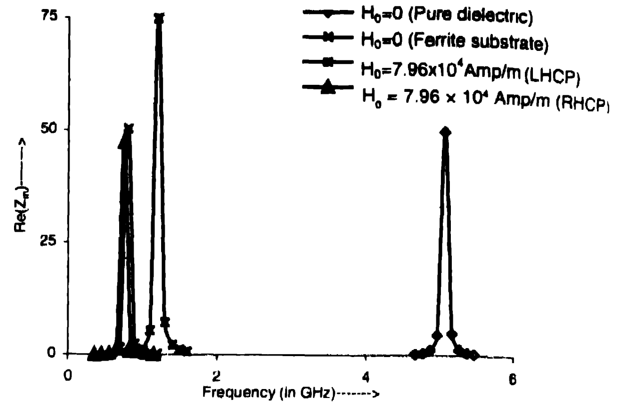

Figure 4. Variation of real input impedance of antenna with frequency under biased and unbiased conditions.

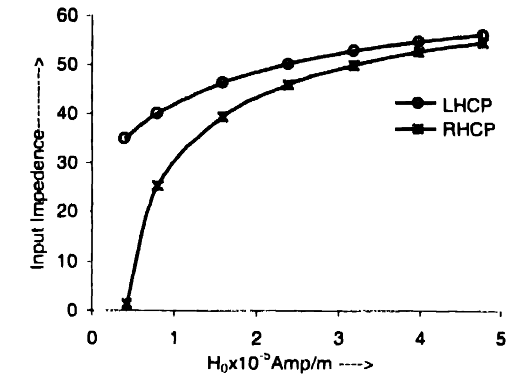

Figure 5. Variation of input impedance of antenna with applied bias field in TM_{11} mode of excitation

The variation in quality factor, directivity and bandwidth of ferrite based RITMA structure with applied magnetic field is shown in Table 3. The total quality factor of antenna has been computed by duly considering dielectric, magnetic, conductor and radiation losses involved with antenna structure. It can be seen from Table 1 that total Q factor of antenna designed on

Table 3. Variation of different parameters of ferrite based RITMA structure with magnetic field.

$a = 0.026$m, $\varepsilon_r = 14.78$, $h = 0.002$ meter, $\mu_0 M_s = 0.3$ Tesla

S No	Applied field ($\times 10^5$ Amp/m)	Quality factor LHCP Mode	Quality factor RHCP Mode	Directivity (in dB) LHCP Mode	Directivity (in dB) RHCP Mode	Band width (%) LHCP Mode	Band width (%) RHCP Mode
1	0 427	20.05	18 95	4 84	4 77	3.526	3.730
2	0.796	20 01	20.12	4.86	4 81	3 533	3.510
3	1.194	19 98	20 06	4 88	4 83	3.539	3.524
4	1 989	19 93	19 98	4 90	4.87	3.540	3 538
5	2.785	19 90	19.93	4.92	4.90	3.553	3.547
6	3 581	19.88	19.90	4 93	4 92	3.557	3.553
7	4.377	19.87	19.88	4.94	4.93	3 561	3.557

ferrite substrate is quite low in comparison to antenna designed on non-magnetic substrate. This indicates that ferrite-based antenna is radiating more effectively. The quality factor of antenna in LHCP mode systematically decreases with increasing applied magnetic bias field however in RHCP mode it increases first but later decreases on increasing applied magnetic field.

The variation of bandwidth with applied magnetic field as shown in Table 3, indicates in LHCP mode bandwidth of antenna increases on increasing the applied magnetic field however in RHCP mode bandwidth of antenna first decreases but later marginally increases. The maximum bandwidth up to 3.73% may be achieved for RHCP mode at DC bias field $H_0 = 4.27 \times 10^4$ Amp/m. It states that by applying a ferrite material in place of a non-magnetic material in antenna designing, a higher bandwidth may be achieved. No large change in the directivity of antennas recorded however antenna in LHCP mode is little more directive than in RHCP mode.

4. Conclusions

The radiation properties of a right isosceles triangular microstrip antenna printed on a magnetically biased ferrite substrate are investigated theoretically in this paper and some important results are recorded. As shown in Table 1, instead of applying low permittivity nonmagnetic, isotropic substrate, an externally magnetized ferrite substrate may be used in antenna preparation to get better radiation characteristics. Under application of proper magnetic field and circular polarization mode, low value of quality factor and large directivity can also be obtained. Several other results including off switch limitations of this antenna are also reported in this paper.

Acknowledgments

The authors are thankful to Dr. S Pal, Dr. Lakshmeesha of ISAC Banglore for granting permission to use simulation software at their center and to Mr. Praveen Kumar for his help during execution. Authors are also thankful to Dr. S. Raniwala for sparing computation facilities from his Department of Science & Technology (DST) sponsored project. One of us (VKT) is thankful to the Council of Scientific & Industrial Research (CSIR), New Delhi, for awarding the research fellowship to carry out this work.

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